Analog Ultra-High Speed Thyristor Design Based on Baker Anti-Saturation Circuit

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Abstract. The turn-on time of ordinary thyristors is affected by the distribution parameters and the positive feedback process, and the turn-on time is longer. At the same time, due to the saturation of the internal transistors, the carriers in the three conductive regions accumulate, which results in a long carrier recombination time during turn-off, so the thyristor turn-off time is also very long. In order to solve the problem of slow speed of common thyristor switch, this paper designs an analog ultra-high-speed thyristor with thyristor characteristics. The analog ultra-high-speed thyristor is composed of fully discrete devices, using symmetric Baker anti-saturation clamp. The circuit clamps the tube voltage drop of both transistors to about 1.4V, and the transistor does not enter saturation, which greatly increases the switching time. The measured results show that the analog ultra-high-speed thyristor has an on-time of less than 30 ns and a turn-off time of less than 50 ns. The switching speed is about two orders of magnitude higher than that of the high-frequency thyristor, and provides an idea for the design of high speed power devices and the tube drop clamp of transistors.

1. Introduction
Thyristors, also called silicon controlled rectifier, are referred to as SCR. Since the birth of thyristors, they have been widely used in a variety of applications requiring rectification. In some low frequency applications, the voltage and current that the thyristor can withstand is still the highest in the existing electronic devices, and the reliability is also high. However, in some occasions where the switching speed is very high, the switching speed of the thyristor cannot meet the requirements [1]. To this end, this paper studies a simulated ultra-high-speed thyristor composed of fully discrete devices, which uses a symmetric Baker anti-saturation circuit to change the thyristor structure, so that it can reduce the factors affecting its turn-on and turn-off time;

This paper focuses on the composition of the designed thyristor, the factors affecting the speed of the thyristor switch, and the working principle of the symmetrical Baker anti-saturation circuit. The experimental situation of the above-mentioned simulated ultra-high-speed thyristor is also introduced.

2. Status Analysis
In the prior technology, the upper limit of the operating frequency of a common thyristor is about several kilohertz. Although there are high frequency thyristors and fast thyristors that can work in high frequency applications, the upper limit of the working frequency of fast thyristors or high frequency thyristors is only a few tens of kilohertz, and the switching time is on the order of microseconds,
which is difficult to use in applications where the switching speed is high [1]. In the existing market products, although the die structure and manufacturing process of the common thyristor are improved, the common thyristor still needs hundreds of microseconds in the off time, while the fast thyristor needs several tens of microseconds, even a high-frequency thyristor takes about 10 microseconds. In some cases where the switching speed of the thyristor is required to reach 1-2 microseconds or higher, the existing products cannot meet the requirements [1].

3. Factors Affecting The Switching Speed

The thyristor is a P1N1P2N2 four-layer three-terminal structure component with three PN junctions packaged as a whole. The specific working process can be simulated by two combined transistors [1][2]. The transistor is a semiconductor device that relies on carriers to participate in conduction. Three doped regions are formed on the same silicon wafer according to different doping modes, that is, three conductive regions of the transistor [2].

3.1. Turnoff process

As shown in Fig.1,

![Figure 1](image)

Figure 1. Ordinary thyristor equal circuits

After the trigger signal is applied from the trigger electrode G, the transistor V2 is turned on, and the collector current of V2 is injected into the base of the transistor V1. After the V1 is turned on, the collector current flows in again as the base current of the transistor V2, and the inside forms a strong positive feedback, maintain the conduction state[1-2]. However, the positive feedback of the transistor will cause the tube voltage drop of the transistor to decrease, the amplification of the transistor will be weakened, and the saturation trend will further lead to the long positive feedback time of the thyristor. In addition, due to the distribution parameters of the circuit wires and the time constant of the external circuit, the accumulation of carriers inside the transistor is slow, and the current of the transistor needs to be a period of time from the conduction to the operating current, and it takes a certain amount of time for two thyristors to reach the interlock, so the thyristor has a longer turn-on time.

3.2. Shutdown process

When the transistor is in the amplified state, the base current will increase, the collector current will also increase, and the collector potential will decrease. When the collector potential drops below 0.7V, the collector junction will change from reverse bias to forward bias, from the amplified state to the saturated state. At this time, the base current will lose control of the collector current. The thyristor will enter saturation. The current flowing into and out of the transistor is limited by the circuit rules of the external circuit, so the carriers will accumulate in the three conductive regions. At this time, a back pressure is applied between the anode and the cathode, and the thyristor does not turn off immediately. Since a large number of carriers accumulated in the three conductive regions of the transistor can only
be reduced by recombination, and this recombination process is also a long process, the turn-off time of the thyristor becomes longer.

Therefore, the turn of the thyristor is affected by the distribution parameters and the carrier accumulation speed. The speed cannot be fast, usually takes several tens of microseconds. And when it is turned off, it is affected by the saturation state of the transistor, and it cannot be fast, usually up to one hundred microseconds. So it is more difficult to increase the switching time of the thyristor by an order of magnitude.

4. Symmetric Backer Anti-Saturation Circuit

By analyzing the switching process of the transistor, it can be known that the key to the problem that the thyristor needs to be fast switched is how to keep the transistor from going into saturation and continue to work in the amplified state. The ultra-high-speed thyristor designed in this paper uses the symmetric baker anti-saturation circuit to solve the problem that the transistor is extremely saturated [3-5]. As shown in Fig.2,

![Figure 2. Baker resistance of saturated circuits](image)

The symmetrical Baker anti-saturation circuit consists of five Schottky diodes VD1, VD2, VD3, VD4, VD5 with a voltage drop of 0.7V and resistor R3.

4.1. Conduction situation

When an on-signal is applied between the base of the transistor V2 (NPN tube) and the launching stage and the signal voltage amplitude reaches 0.7V, the transistor V2 turns on. Due to the clamping action of the diodes VD4 and VD5, the collector potential of the transistor V1 and the voltage of R3 are not counted, so

\[ V_{c1} = V_{be2} + V_{VD4} + V_{VD5} = 0.7V + 0.7V + 0.7V = 2.1V \]

The collector potential of the transistor V1 is at least 2.1V, the diode VD3 is clamped, and the collector potential of the transistor V2 is

\[ V_{c2} = V_{c1} - V_{VD3} = 2.1V - 0.7V = 1.4V \]

The tube voltage drop of transistor V2 will be 1.4V, which will be slightly higher (taking into account R3 voltage). Then transistor V2 will not enter saturation, but will always work in the amplified state. After the transistor V1 turns on, the base potential

\[ V_{bl} = V_{c1} + V_{VD1} + V_{VD2} = 1.4V + 0.7V + 0.7V = 2.8V \]

And after the transistor V1 (PNP tube) turns on, launching potential
\[ V_{el} = V_{bl} + V_{bel} = 2.8v + 0.7v = 3.5v \]

The tube voltage drop of the transistor V1 is
\[ V_{cel} = V_{el} - V_{c1} = 3.5v - 2.1v = 1.4v \]

Therefore, through the voltage clamping function of the symmetric baker anti-saturation circuit, as long as the circuit turns on, the voltage drop of the two power main switch transistors is always clamped at about 1.4V, not entering saturation and always working in the amplified state.

**Figure 3.** A model of analog ultra-high speed thyristor

4.2. Tube Pressure Drop Clamping Process
After the ultra-high speed thyristor turns on, the collector potential \( V_{c2} \) of the transistor V2 is about 1.4V. The anode potential \( V_{c1} \) of the diode VD3 is 2.1V, and the base potential \( V_{b1} \) of the transistor V1 is 2.8V. Assuming that the tube voltage drop of transistor V2 rises, i.e., the collector potential \( V_{c2} \) increases, the current of diode VD3 will decrease. Since the anode and cathode potential differences are reduced, the difference between the base potential \( V_{b1} \) of the transistor V1 and the collector potential \( V_{c2} \) of the transistor V2 is also reduced, and the anode and cathode potential differences of the diodes VD1 and VD2 are also reduced. The external circuit current is shunted from the base branch of transistor V1 and the collector branch of V2. As the base current and collector current of V2 both increase, the collector potential \( V_{c2} \) will decrease. When the collector potential \( V_{c2} \) is reduced to about 1.4V, the currents of the diodes VD1, VD2, and VD3 will return to normal values, and the collector potential \( V_{c2} \) of the transistor V2 will continue to remain at about 1.4V. As long as the collector potential \( V_{c2} \) of the transistor V2 is maintained at about 1.4V, and the base potential \( V_{b1} \) of the transistor V1 is only about 2.8V, the tube voltage drop of the transistors V1 and V2 is maintained at around 1.4V by the negative feedback of the diodes VD1, VD2, and VD3.

5. Design Of Analog Ultra-High Speed Thyristor
This paper proposes a scheme for analog ultra-high-speed thyristors using fully discrete devices, as shown in Fig.3. The analog ultra-high-speed thyristor has thyristor characteristics and is a fully-controlled power device. It consists of two directly coupled power switching transistors V1 and V2 with deep positive feedback and baker anti-saturation clamp circuit [4-5]. The diodes VD1, VD2, and VD3 form a voltage parallel negative feedback, so that the turn-on voltage drop of the two power main switching transistors is always clamped at about 1.4V, and the working state is always in an amplified state, and does not enter a saturated state, thereby achieving a great increased speed of the thyristor switch.
5.1. Structure of ultra-high speed thyristor
As shown in Figure 3, the resistors R1, R2, and R3 act as anti-interference, and the resistor R4 (several hundred ohms) acts as a current limiting. And the switching frequency of the five Schottky diodes is high, and the reverse recovery time is only tens of nanoseconds. Thus, if the characteristic frequency of the two power main switching transistors is 100 MHz, the theoretical maximum switching speed of the analog ultra-high speed thyristor can reach 2.5 to 5.0 ns [4-5].

5.2. Structure of symmetric baker clamp circuit
The potential clamp requires a feedback component, the collector of transistor V2 is connected with a diode VD3. As described above, when the collector potential V_{c2} of the transistor V2 is increased, VD3 acts as V_{c2} feedback element and is clamped by the shunt size of the diode VD3. V_{c2} is 1.4V during normal conduction. Due to serialization into VD3, the collector potential V_{c1} of transistor V1 is 2.1V, and the V_{be2} of transistor V2 is 0.7V. Therefore, two diodes VD4 and VD5 are connected in series at the base of transistor V2.

5.3. Experimental data
Under the action of 25 KHz PWM wave, the ultra-high speed thyristor has a turn-on time of 30ns and a turn-off time of about 10ns. The switching speed is about two orders of magnitude higher than that of high-frequency thyristor [4] [5].

Fig.4 shows the measured ultra-high speed thyristor turn-on waveform, and Fig.5 shows the turn-off waveform.

![Figure 4. The turn-on waves of the analog ultra-high speed thyristor](image1)

![Figure 5. The turn-off waves of the analog ultra-high speed thyristor](image2)

In the turn-on and turn-off waveform diagrams, the ordinate indicates the voltage drop of the ultra-high-speed thyristor, where the ground symbol in the ordinate represents the 0 potential point. The
abscissa represents the time axis. In the turn-on waveform, the ordinate represents 3V per grid, and the abscissa represents 10 ns per grid. In the turn-off waveform, the ordinate represents 3V per grid, and the abscissa represents 5 ns per grid.

5.4. Actual constraints
When actually making and connecting circuit components, there are distributed parameters such as distributed inductance and distributed capacitance in wire. The influence of distribution parameters on the switching time of analog ultra-high-speed thyristors cannot be negligible. And there are also structural effects when wiring the circuit board. Therefore, it is only possible to make the switching time of the analog ultra-high speed thyristor close to the theoretical switching time when the distribution parameters are lowered and the wiring of the board is reasonable.

6. Conclusion
Experiments show that after using a fully discrete device to form an analog ultra-high-speed thyristor, the baker anti-saturation clamp circuit clamps the transistor's tube voltage drop, allows the transistor to never enter saturation after being turned on, and always works in an amplified state, which has improved the switching speed of analog ultra-high speed thyristors. However, due to the influence of circuit connection and distribution parameters, the theoretical switching time may not be achieved. At present, the analog ultra-high-speed thyristor turn-on time is less than 30 ns, and the turn-off time is less than 50 ns. It has been increased by about two orders of magnitude compared with the switching time of ordinary thyristors, which greatly improves the switching speed and meets the design requirements. Moreover, the ultra-high-speed thyristor designed in this paper has obtained the invention patent and utility model patent, which proves the feasibility of the design, provides a design method for the design of high-speed power devices, and also provides a design for the tube voltage drop clamp of the transistor.

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