Modeling and Experiment Research on Turn-off Characteristics of Pulsed Power Thyristor

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Abstract—**Pulsed power thyristors have been widely used in pulsed power systems due to their controllability, large through-flow capacity and high repetition frequency. To study the device's electrical characteristics and the circuit transient process, based on research of reverse recovery process of pulse thyristor, a macro model of pulsed power thyristor applying to MATLAB/Simulink software platform was established in this paper. This model combined ideal thyristor model in MATLAB with reverse recovery current module, which was designed to describe the reverse recovery process of thyristor after the conducting current rapidly decreased to zero. In the model, reverse current increased with a constant *di/dt* when accumulated carriers rapidly decreased; and then when space charge region started to recover, the thyristor's recovery current curve was described by two hyperbolic secant curves with different time constant. This established model achieved the smooth transition of current curve from storage time to dropping time, and thus improving the precision of thyristor model comparing with the model provided by Simulink library. In addition, experiment was designed to verify the macro model. According to the experimental data, the reverse recovery voltage and recovery current curve calculated by the macro model fitted well with the experiment results.**

Keywords—thyristor; turn-off characteristics; modeling; MATLAB

I. INTRODUCTION

The pulsed power thyristor has been widely used as main switch in pulsed power systems for its good controllability, large through-flow capacity and high repetition frequency. However the existence of reverse recovery characteristics during turn-off process may lead to overvoltage on the thyristor which can damage the device irreversibly [1-2]. As shown in Fig.1, a high power pulse thyristor valve was broken down by overvoltage during the discharge process of a pulsed power circuit. Such damage not only causes economic losses but also brings about a great threat for researchers. To accurately explain the cause of thyristor's breakdown, it is necessary to have a further understanding of its turn-off process. Theoretical analysis and experimental research are made in this paper. Besides, since the thyristor model provided by simulink library does not have a reverse recovery process [3], an improved thyristor model for high voltage and high current transient simulation is proposed based on the external characteristics of the device, using Matlab/Simulink software . To be specific, the improved model mainly focuses on the turn-off process of the thyristor intending to precisely describe the characteristic of thyristor's current and voltage.

Fig. 1. Structure of a damaged thyristor valve with a specific gate structure designed to make the whole chip area ignited in a few microseconds [1].

II. THEORETICAL ANALYSIS

Pulse thyristors are solid-state semiconductor switches that structurally have three terminals and four layers. A standard one dimensional physical structure of PNPN pulse thyristor is shown in Fig. 2. The charge distribution profile in the device geometry is discretized into fourl critical regions, along with the current flows through the thyristor, large quantity of carriers are accumulated in these PN junctions [4].

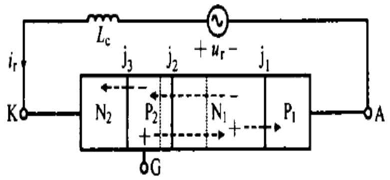

Fig. 2. One dimensional PNPN pulse thyristor physical structure with external circuit. A is anode of thyristor; K is cathode and G is gate. j_1~j_3 represent three PN junctions. L_C represents the inductor in series with the pulse thyristor and u_r is the voltage source in the circuit. i_r is the curent that flows through the thyristor. Arrows represent the movement of hole charges and electron charges.

As forward current decreases to zero, the device continues to conduct due to excessive carriers remaining in the PN junctions, which is called the reverse recovery process [5]. These carriers require a certain time to be removed by reverse current flow and by recombination with opposite charge carriers. Fig. 3 shows the change trends of time-dependent current and voltage when thyristor turns off with I_{RM} and V_{RRM} the peak reverse recovery current and reverse voltage, respectively. The reverse recovery process causes the voltage of inductor in series with the thyristor to increase to a relatively high voltage when reverse current sharply decreases from I_{RM} to zero. This leads to reverse overvoltage of the thyristor [6-9].

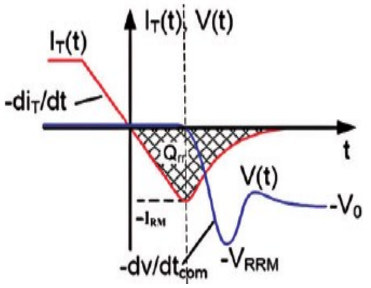

Fig. 3. Turn-off process of thyristor, I_{RM} is the peak value of reverse recovery current. V_{RRM} is the peak value of reverse voltage.

III. EXPERIMENTS AND RESULTS

A. *Experimental setup*

A pulse forming unit is established to measure turn-off characteristics of pulse thyristor. The experimental schematic is shown in Fig. 4. We neglect stray inductance and resistance.

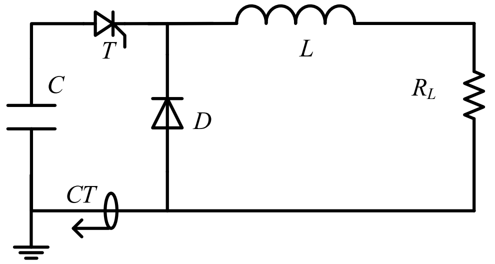

Fig. 4. Experimental schematic diagram. T is the tested thyristor with a rated voltage of 5.2 kV and capable of switching up to 150 kA with a maximum di/dt of 3000 A/μs; D is the diode; C is the capacitor (1785μF); L is the inductor (10μH); R_L is the load resistor (5mΩ); CT is the current probe. The charging voltage of capacitor is gradually promoted in a range of 200V to 4000V.

The stability of the current probes is the key factors affecting the accuracy of the measurement, especially the accuracy of current during reverse recovery process. In experiments, the current probe was filled with flexible foam to make sure the cable locate in the middle of the circular probe

B. *Experimental results*

The reverse recovery current of pulse thyristor is measured by two current probes synchronously as contrast while the entire current is measured by another current probe at the same time. Besides, a high voltage probe is used to measure the reverse recovery voltage of thyristor. Typical entire current waveform of thyristor in PFU is shown in Fig. 5. It shows the peak value of on-state current of thyristor I_F and the changing trend of thyristor during the entire process. Fig. 6 shows the typical current and voltage waveforms of thyristor in reverse process.The fall rate of thyristor's current di/dt at the moment of zero-crossing is calculated, so does the reverse recovery charge Q_{rr}. Table I shows the experimental data that related to thyristor reverse process.

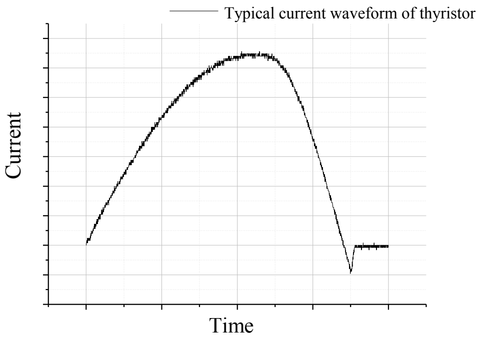

Fig. 5. Typical current waveform of thyristor in PFU

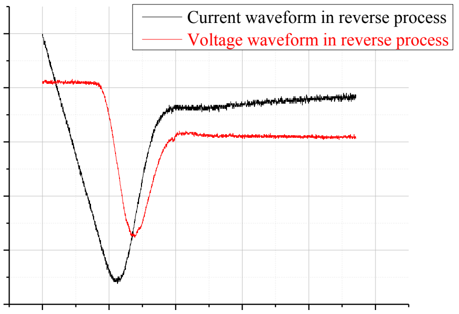

Fig. 6. Typical current and voltage waveforms of thyristor in reverse process

TABLE I. EXPERIMENTAL DATA

Charging voltage (V)	**I_F (kA)**	**I_{RM} (kA)**	**V_{RRM} (V)**	**di/dt (A/μs)**	**Q_{rr} (μC)**
200	2.04	0.481	228	27.14	8456
500	5.32	0.972	508	70.38	15003
1000	10.7	1.65	976	145.75	21812
1500	16.2	2.19	1480	222.19	26064
2000	21.8	2.715	1900	299.04	28852
2500	27	3.185	2340	375.49	31880
3000	32.8	3.6	2760	455.0	33650
3500	38.4	4.015	3160	537.37	36006
4000	43.6	4.45	3520	611.73	39714

C. *Experimental results analysis*

1) Relationship between I_F and di/dt

Fig. 7 shows our initial assessment of I_F and *di*/*dt* for studying the the turn off process of the thyristo.

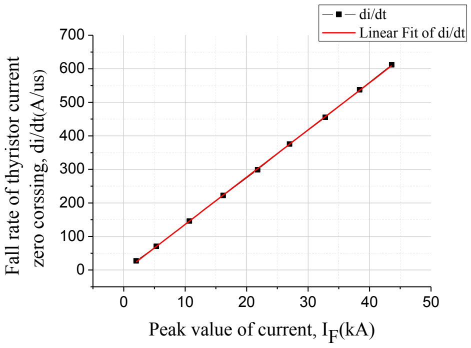

Fig. 7. Relationship between I_F and di/dt

Fig. 7 shows that I_F and di/dt are linearly related, so they can be considered as a single parameter when deriving their relationships with I_{RM} and Q_{rr}. This means that $Q_{rr}=f(di/dt, I_F)$ can be simplied as $Q_{rr}=f(di/dt)$.

2) Derivation of I_{RM} and Q_{rr}

According to Table I, Q_{rr} can be fit as

$$Q_{rr} = 3\times10^{-4}\left(\frac{di}{dt}\right)^3 - 0.3334\left(\frac{di}{dt}\right)^2 + 156.8\frac{di}{dt} + 4913.8 \tag{1}$$

and I_{RM} can be fit as

$$I_{RM} = -5\times10^{-6}\left(\frac{di}{dt}\right)^2 + 0.0095\frac{di}{dt} + 0.295 \tag{2}$$

These expressions can be used to describe the turn off process of the thyristor.

IV. MODELING AND SIMULATION

A. Modeling

A macro model is built to simulate the turn-off process of pulse thyristor based on the Matlab system simulation platform. The macro model uses conventional devices to describe the external behavior of the thyristor. The thyristor's hyperbolic secant model created by Matlab/simulink consists of two parts, as shown in Fig. 8. In the structure diagram, T represents the original thyristor device from the power system blockset which is only able to simulate the forward through-flow of thyristor, while I_R represents reverse recovery current that controlled by devices from relevant blockset.

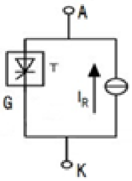

Fig. 8. Structure diagram of macro model of thyristor.

A piecewise function with three stages is proposed to describe the reverse current of thyristor is given by [10]

$$I_R(t)=\begin{cases} -t*di/dt & t\le t_c \\ -I_{RM}*sech\left[(t-t_2)/\tau_a\right] & t_c<t\le t_2 \\ -I_{RM}*sech\left[(t-t_2)/\tau_b\right] & t>t_2 \end{cases} \tag{3}$$

In (3), τ_a and τ_b are time constants; t_c is the moment that current changing rate changes; t_2 is the moment that the reverse current reaches its maximum.

According to (3), reverse recovery current is determined by di/dt, I_{RM}, τ_a, τ_b and t_2.

After derivation, t_2 , τ_a, τ_b can be calculated as

$$t_2=\tau_a*\mathrm{sech}^{-1}(0.8)+t_c \tag{4}$$

$$t_c=0.8*I_{RM}/(di/dt) \tag{5}$$

$$\tau_a=2*\frac{I_{RM}}{di/dt}*\frac{e^{\mathrm{sech}^{-1}(0.8)}-e^{-\mathrm{sech}^{-1}(0.8)}}{\left(e^{\mathrm{sech}^{-1}(0.8)}+e^{-\mathrm{sech}^{-1}(0.8)}\right)^2} \tag{6}$$

$$=0.48*\frac{I_{RM}}{di/dt}$$

$$\tau_b=\left(\frac{Q_{rr}}{I_{RM}}-\frac{I_{RM}}{2\frac{di}{dt}}\right)*\frac{2}{\pi} \tag{7}$$

Using (1) and (2), one can obtain I_{RM}, τ_a, τ_b and t_2 once di/dt is obtained in simulation.

B. Simulation

We simulate the experiment circuit by creating a thyristor model based on the MATLAB system simulation platform. Fig. 9 shows full simulation results of thyristor's current and voltage while Fig. 10 shows the curent and voltage waveforms during reverse process. Furthermore, Fig. 11 compares experimental and simulated current while Fig. 12 compares experimental and simulated current and voltage during the reverse process. Table II lists related simulation and test data.

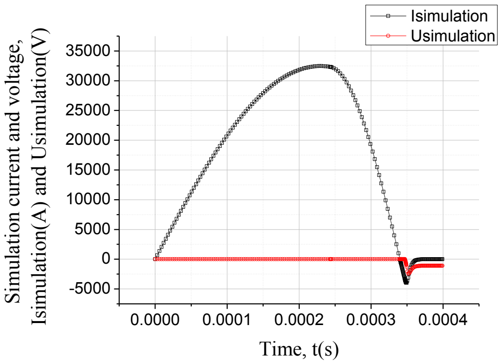

Fig. 9. Full simulation results with charging voltage 3000V

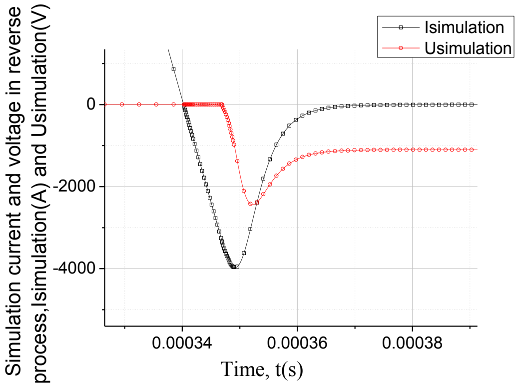

Fig. 10. Simulation results during reverse process with charging voltage 3000V

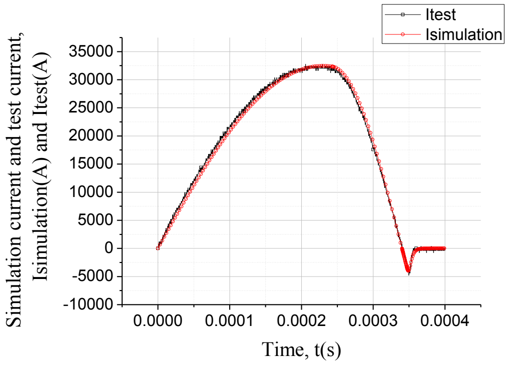

Fig. 11. Comparison between experiment current and simulation current

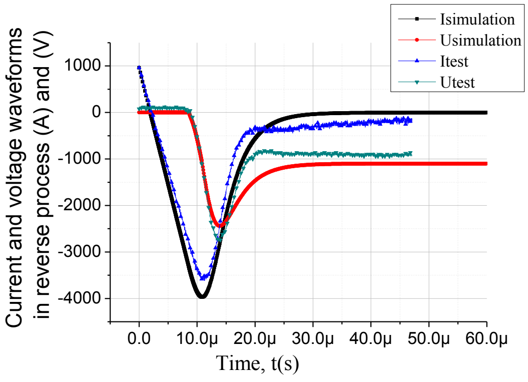

Fig. 12. Comparison between experiment results and simulation results during reverse process

According to Fig. 11 and Fig. 12 and Table Ⅱ, it is well-founded that simulation current waveforms are approximately the same as experiment current waveforms in aspects of pulse width and peak value of on-state current I_F and reverse current I_{RM}. As for peak value of reverse voltage V_{RRM}, simulation data are lower than test data since simulated reverse current takes longer time to return block. Within the margin of error, it can be demonstrated that hyperbolic secant model build in this paper can approximately describe the reverse current of pulse thyristor and it can be applied to power system simulation.

TABLE II. EXPERIMENTAL DATA

Charging voltage （V）	I_F（kA）		I_{RM}（kA）		V_{RRM}（V）	
	Test data	***Simulation data***	***Test data***	***Simulation data***	***Test data***	***Simulation data***
1000	10.7	10.67	1.65	1.645	976	812
1500	16.2	16.01	2.19	2.232	1480	1226
2000	21.8	21.35	2.715	2.765	1900	1667
2500	27	26.68	3.185	3.243	2340	2098
3000	32.8	32.03	3.6	3.648	2760	2465
3500	38.4	37.36	4.015	4.007	3160	2729
4000	43.6	42.704	4.45	4.305	3520	2859

V. CONCLUSIONS

This paper mainly works on turn-off characteristics of pulse power thyristor. A pulsed forming unit is established to measure turn-off characteristics of thyristor. The results indicate that the changing rate of current decreasing to zero (*di*/*dt*) has a linear relationship with peak value of on-state current (I_F). Hyperbolic secant model can approximately describe the reverse current of thyristor .

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