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Analysis of Thyristor failure in Hybrid Energy Storage System

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***Abstract*—This paper introduces a new energy storage method consists of "battery + pulse capacitor", which reduces the power requirements for shipboard railgun to power grid. First the model of hybrid energy storage is built based on the course of discharging, then peak value of the current when battery charges capacitor is calculated out by theoretical derivation, and a constant current charging method is designed. On this basis, simulation is carried out under the condition that the thyristor fails short, the results show that the failure will damage the system, based on this, this paper design a method of protecting the system from overcurrent damage.**

Keywords- Shipboard railgun, hybrid energy storage, high-powered pulse power, thyristor failure.

I. INTRODUCTION

"Chemical stored energy + physical stored energy" mode is adopted to increase instant power in new-style hybrid energy storage technology, which decreases the power need of shipboard railgun to power grid, this mode takes full advantages of high energy density for chemical stored energy and high power density for physical stored energy. The basic principle is that energy from power grid is firstly transferred to battery within a relatively long time, and then the energy is transferred to capacitors within a short time, after that capacitors discharge to electronic load quickly [1], accordingly the instantaneous power is amplified [2]-[3]. Academician Ma Weiming from Naval University of Engineering put forward that shipboard railgun should use hybrid energy storage for power supply, and led the development of correlation studies [4].

During the course of energy transferring, thyristor is the switch. Compared with the conventional air gap switch, semiconductor switch is advantage at opening speed, high output power, small volume, operational life span and so on. So it is widely applicable. But it can't physically isolate the high voltage once it breakdowns.

First, the mathematical model of the hybrid energy storage system is built in this paper. Then the time variant expression of the current of the main circuit is deduced, the peak value of current is calculated out. Based on that, a constant current charging method is designed, then the paper analyzes the condition that thyristor in high-powered pulse power fails short, the results show that the failure will damage the system, based on this, this paper design a method of protecting the system from overcurrent damage. Simulations are carried out to test the method.

II. WORKING PRINCIPLE AND MODELING ANALYSIS OF HYBRID ENERGY STORAGE SYSTEM

The circuit diagram of the hybrid energy storage system is presented in Fig. 1, which is composed of the battery, the high voltage switch, the pulse capacitor, the thyristor, the launching device is expressed as R.

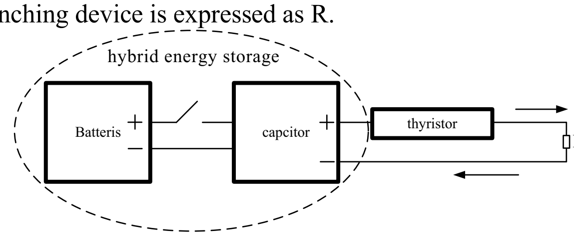

Figure 1. The main consist of hybrid energy storage

In fig. 1, the high voltage switch is switched on, after the capacitor is charged, switch off the high voltage switch, then trigger the thyristor, the capacitor discharge to launching device R. a constant current charging method is adopted in this paper, multiple groups of batteries are used in series, and every group of battery is cascade into the circuit in designed sequence. The voltage steps up to charge the capacitor.To simplify the analysis, the hybrid storage system consist of one group battery to one pulse capacitor is shown in Fig.2.

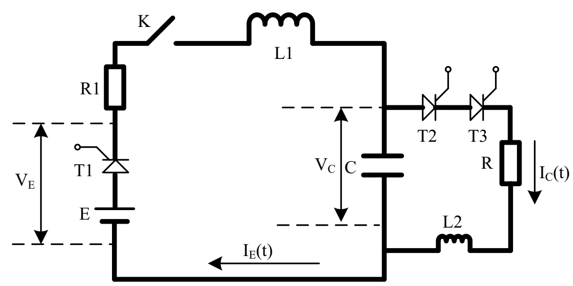

Figure 2. The electronic circuit of hybrid energy storage unit

In Fig.2, because the work voltage will reach 10kV, current through R will reach 35kA, conventional thyristor is hard to support this voltage and current at the same time, so two high-powered thyristor whose forward voltage are 8kV are used in series in hybrid storage system.

The hybrid energy storage system works according to the following process. First, K is switched on. Then T1 is trigged on, which will enable the energy transfer from E to C and the current $I_E(t)$ will gradually increase. If the voltage across the capacitor V_c increase to a specific value, the current starts to decrease, and the peak value of $I_E(t)$ will be efficiently reduced due to the existence inductor L.

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Moreover, the energy stored in the inductor can only transfer into the capacitor because of the unidirectional characteristic of the thyristor, which means that the voltage of the capacitor V_c will be higher than the voltage of the battery V_E eventually. After the capacitor is charged, switch off the high voltage switch K, trigger T2 and T3, capacitor discharge to R.

First analyze the course energy transfer from battery to capacitor, $R1 = 10mW$, $L1 = 400mH$, $C = 100mF$, $V_{E0} = 1000V$, $R = 30mW$, $L2 = 100uH$, the following equation holds for the circuit shown in fig. 2 according to Kirchhoff Voltage Law.

$$R1 I_E(t) + L1\frac{dI_E(t)}{dt} + \frac{1}{C}\int_0^t I_E(t)dt - V_{E0} = 0 \quad (1)$$

Applying differential calculation to the both sides of Eq. 1, the following equation can be obtained.

$$L1 I_E'' + R1 I_E' + \frac{1}{C} I_E = 0 \quad (2)$$

As the given system is under-damped, then $R1 < 2\sqrt{\frac{L1}{C}}$ holds and the solution to the above second order linear homogeneous differential equation can be resolved as Eq. 3.

$$I_E(t) = [I_1 \sin wt + I_2 \cos wt]\exp(-\frac{t}{t}) \quad (3)$$

In Eq. 3, the time constant is $\tau = \frac{2L1}{R1}$ and the resonance frequency is $\omega = \frac{1}{L1}\sqrt{\frac{L1}{C} - \frac{R1^2}{4}}$. Substituting equation $I_E(0) = 0$ to Eq. 3, the solution can be simplified as Eq. 4.

$$I_E(t) = (I_1 \sin wt)\exp(-\frac{t}{t}) \quad (4)$$

Let $dI_E(t)/dt = 0$, then the time when $I_E(t)$ reaches its maximum value can be calculated as Eq.5.

$$t_m = \frac{1}{\omega}\tan^{-1}(\omega\tau) \quad (5)$$

Then the capacitor voltage at time t_m can be obtained as following.

$$V_C = \frac{1}{C}\int_0^{t_m} I_E(t)dt = \frac{I_1}{C}\int_0^{t_m}\left[(\sin wt)\exp(-\frac{t}{t})\right]dt \quad (6)$$

Using the method of integration by parts, the integration section of Eq. 6 can be calculated as following.

$$\int_0^{t_m}\left[\sin\omega t\cdot\exp(-\frac{t}{\tau})\right]dt = \frac{1}{\omega}\left[1-\exp(-\frac{t_m}{\tau})\left(\cos\omega t_m + \frac{\sin\omega t_m}{\omega\tau}\right)\right] - \frac{1}{\omega^2\tau^2}\int_0^{t_m}\exp(-\frac{t}{\tau})\sin\omega t dt \quad (7)$$

Then it can be obtained that,

$$\int_0^{t_m}\left[(\sin\omega t)\exp(-\frac{t}{\tau})\right]dt = \frac{\frac{1}{\omega}\left[1-\exp(-\frac{t_m}{\tau})\cos\omega t_m - \frac{1}{\omega\tau}\exp(-\frac{t_m}{\tau})\sin\omega t_m\right]}{1+\frac{1}{\omega^2\tau^2}} \quad (8)$$

Finally, the capacitor voltage can be described as,

$$V_C = \frac{I_1\left[1-\exp(-\frac{t_m}{t})\cos wt_m - \frac{1}{wt}\exp(-\frac{t_m}{t})\sin wt_m\right]}{C\left(w + \frac{1}{wt^2}\right)} \quad (9)$$

At time t_m, the following equation holds.

$$L\frac{dI_E(t)}{dt}\bigg|_{t=t_m} = 0 \quad (10)$$

Then combining Eq. 1, the following equation can be deduced.

$$R1 I_E(t_m) + V_C = V_E \quad (11)$$

Combining Eq. 9 and Eq. 11, I1 in Eq. 6 can be obtained.

$$I_1 = \frac{V_E C\left(w + \frac{1}{wt^2}\right)}{1-\exp(-\frac{t_m}{t})(\cos wt_m - \frac{R1Cw^2t^2 + R1C - t}{wt^2/\sin wt_m})} \quad (12)$$

Then $t = \frac{2L1}{R1} = 80$, $w = \frac{1}{L}\sqrt{\frac{L}{C} - \frac{R^2}{4}} = 5$, $t_m = 1.3133s$ .substitute these parameters in Eq. 12. $I_1 = 499.625$,the peak value of $I_E(t)$ is $I_{Em} = 494.45A$.

To test the calculation results, simulation is carried out and the result is shown as below:

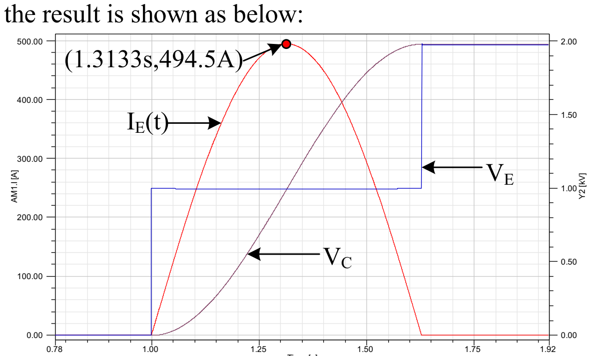

Figure 3. Simulation waveform for hybrid energy storage

In Fig.3,the result is identical to the calculation results. The tigger T2 and T3, the waveform of current from capacitor to R is shown as below:

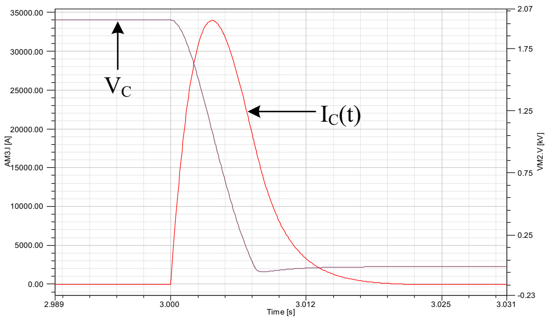

Figure 4. Simulation waveform for pulse capacitor

In Fig.4,the peak value of current from pulse capacitor to R reaches 34kA.

Based on this, multiple groups of battery discharge to pulse capacitor in constant current, the battery groups are cascaded into the circuit in designed sequence. The simulation result is shown as below.

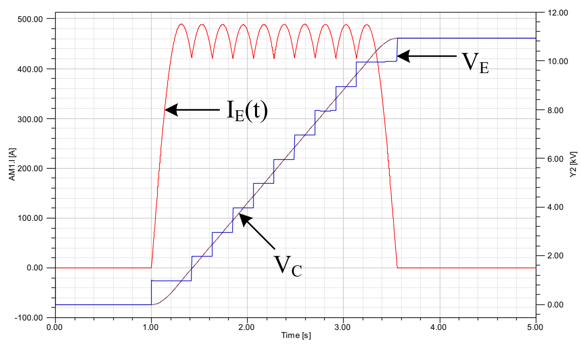

Figure 5. Simulation waveform for ten groups of batteries discharge to pulse capacitor

III. Analysis of Thyristor Failure in High-Powered Pulse Power

When the thyristors T2 and T3 fails, the status of them can be divided as table 1.

Tab.1 Status of thyristor in pulse power source

number	Status of T2	Status of T3
1	normal	normal
2	Fail short	Fail short
3	normal	Fail short
4	Fail short	normal

The status 1 can operate correctly as analyzed before. The status 3 and The status 4 is similar. When the batteries discharge to capacitor, the simulation result is as below.

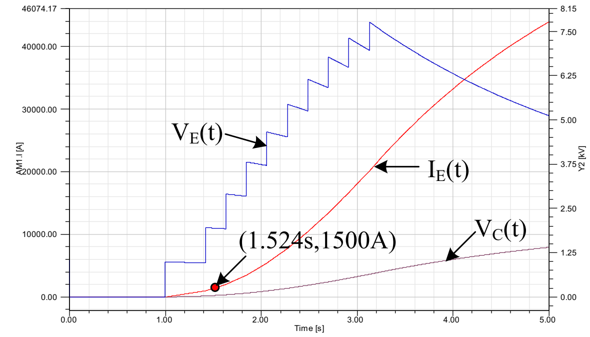

Figure 6. Simulation waveform for hybrid energy storage under status 2

In Fig.6, the batteries discharge to the capacitor and R at the same time, the output current of batteries increases rapidly, at last, the circuit will be burned out.

The status 3 and 4 are similar, when the capacitor is charging, the voltage across the capacitor applies on the normal status thyristor, because the forward voltage of single thyristor is 8kV, when the voltage across the capacitor reaches 8kV, the normal status thyristor breakdown. The whole circuit fail short.

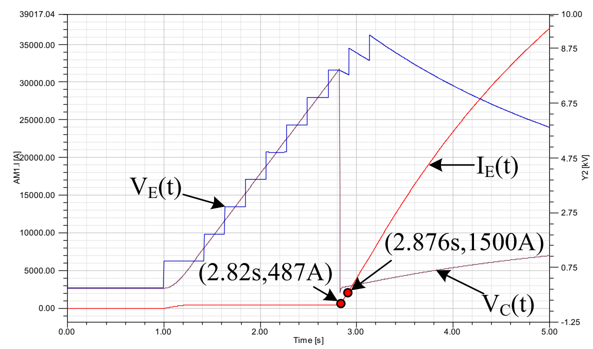

Figure 7. Simulation waveform for hybrid energy storage under condition 3 and 4

In Fig.7,batteries charge the capacitor normally before the voltage across capacitor reaches 8kV, the normal status thyristor breakdown when the voltage across capacitor reaches 8kV, the current from capacitor to launching device R increases rapidly, then the circuit is burned out.

IV. Protect Method from Thyristor Failure

According to the analysis above, the failure of thyristor in high-powered pulse power will result in severe consequence. There must be some method to protect the circuit, the circuit must be cut off when the failure happens. The high voltage mechanical switch can not cut off so large current, so this paper will adopt IGBT to do this, because the work voltage reaches 10kV, multiple IGBT modules are used in series to protect the circuit. Then the current from capacitor is real-time monitored, the IGBT modules cut off the circuit when the current goes beyond.

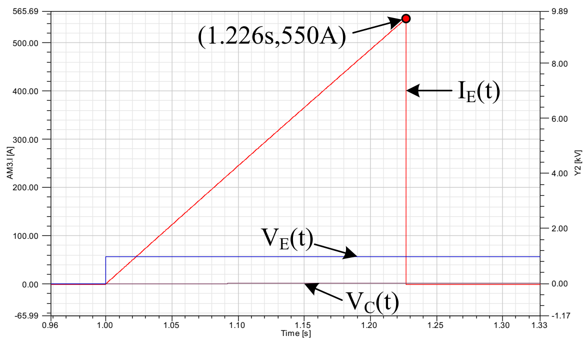

Figure 8. Protection simulation waveform for hybrid energy storage

From Fig. 8, it can be seen that when the current goes beyond to 550A, the IGBT modules cut off the circuit, protect the circuit from damage.

V. CONCLUSIONS

Analysis shows the thyristor failure in high-powered pulse power will result in severe damage, the status of thyristors in high-powered pulse power are important. This paper tries to protect the system from thyristor failure. First, the mathematical model of the hybrid energy storage system is built in this paper. Then the time variant expression of the current of the main circuit is deduced, the peak value of current is calculated out. Based on that, a constant current charging method is designed, then the paper analyzes the condition that thyristor in high-powered pulse power fails short, the results show that the failure will damage the system, based on this, this paper design a method of protecting the system from overcurrent damage by IGBT modules. Simulations are carried out to test the method.

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