A model of Hybrid DC Apparatus Combined with Mechnical switch, Semiconductor Switch and Fuse

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***Abstract*—A hybrid DC electric apparatus was proposed as a protective apparatus for electric vehicles. The topology of the hybrid DC apparatus is a IGBT in series with an DC electric fuse, with which a vacuum interrupter is connected in parallel. The vacuum interrupter, the IGBT and the DC electric fuse were responsible for nominal rated current conduction, overload current interruption and short circuit current interruption, respectively. The objective of this paper is to build up a model for the hybrid DC apparatus. The model of the IGBT, the DC electric fuse and the vacuum interrupter is built up in Simulink/MATLAB separately. The model was experimentally validated. The experimental applied voltage is 500V DC and the current is 100A, 200A, 300A DC, respectively. The simulation result shows that the overvoltage error of IGBT's current interruption is 30%. When an overload current commutated from vacuum interrupter to the IGBT, the current commutation time error was 11.1%. The arcing time error of the DC electric fuse was 3.5%.**

***Keywords*-- Hybrid DC Apparatus, DC Electric Fuse, Current Commutation Characteristics, Modeling**

I. INTRODUCTION

The electric vehicles are developing rapidly all over the world. According to the China's "13th Five-Year Plan"[1], the quantity of electric vehicles in China will reach five millions in 2020. In electric vehicles, the typical protection apparatus include a DC contactor in series with a DC electric fuse. There is one difficulty with the protection apparatus. If an overload current that is 2 times to 5 times of the rated current occurred, both the DC contactors and the DC electric fuse is very hard to interrupt this overload current. It may also cause damage to other apparatus or even cause fire.

Some solutions are as following. MERSEN company developed a combined DC circuit breaker [2], which used a DC switch in parallel with a DC electric fuse. Dai et al developed a hybrid fuse switchgear [3]. The hybrid fuse switchgear has a high speed breaker in parallel with an electric fuse. Liu et al. proposed a hybrid DC circuit breaker[4]. The hybrid DC circuit breaker is composed of a DC switch and a back-up DC fuse in series. HE et al. proposed a topology of DC hybrid circuit breaker[5]. The topology is a fast-switch and a liquid metal fault current limiter in series.

Huang et al. recently proposed a hybrid DC apparatus, as shown in Figure 1[6]. It used a IGBT in series with a DC electric fuse, then a vacuum interrupter is connected with them in parallel. In Figure 1, the vacuum interrupter was used for conducting nominal rated current. The semiconductor switch IGBT was used for overload current interruption. It was normally open. When the nominal rated current or an overload current was to be interrupted, close the IGBT and then open the vacuum interrupter. Thus the current was commutated to the IGBT. After that open the IGBT to interrupt the current. When a short circuit current was to be interrupted, the IGBT kept open and the vacuum interrupter kept close. The short circuit current commutated to the DC electric fuse and the fuse interrupt the short circuit current. Thus the overload current difficulty was solved. A model is desired to understand the hybrid DC apparatus' performance in short circuit current interruptions.

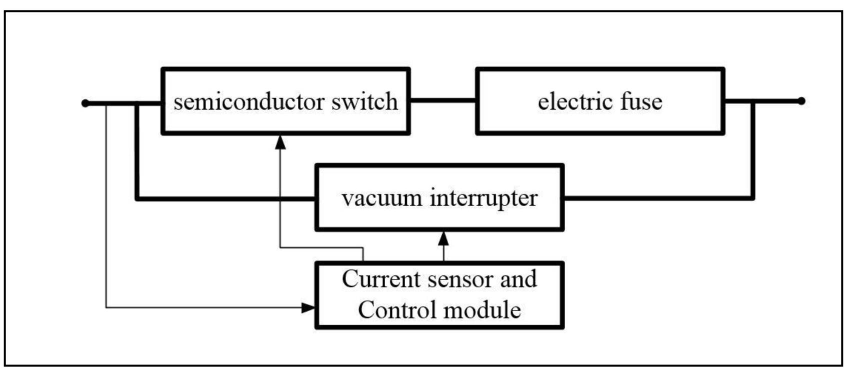

Figure 1. The topology of the DC Interruption Apparatus

The objective of this paper is to build up a model for the hybrid DC apparatus. The model can help to understand the current commutation process in overload current interruption and the short circuit current interruption performance.

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II. The Establishment Of Model

A. Vacuum interrupter Model

A vacuum interrupter normally works in close position, in which it conducts the nominal rated current. In such condition the vacuum interrupter equals to a resistor of several micro ohm. When the vacuum interrupter opens to interrupt a current, an arc is initiated. After current zero, a transient recovery voltage is applied on the vacuum interrupter. If it can withstand the transient recovery voltage, a successful current interruption is achieved. In the topology shown in Figure 1, the vacuum interrupter does not interrupt a current. It is used for conducting nominal rated current and current commutation. Therefore, a model needs to describe the arc voltage of the vacuum interrupter, which drives the current commutation. According to reference [7], the vacuum arc voltage can be modeled by Equation (1). Figure 2 shows the MATLAB/Simulink model of the arc voltage.

$$U_{arc}(\mathrm{t})=U_0+C*V*(t-t_0)*i(t) \qquad (1)$$

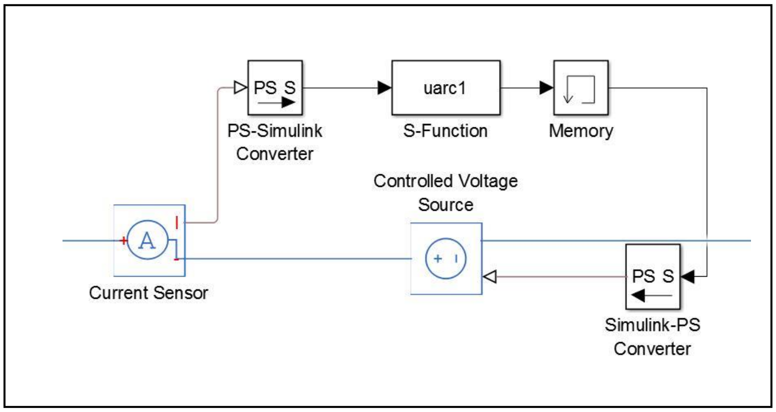


Figure 2. The arc voltage model in simulink/Matlab

B. IGBT Model

The MATLAB/Simulink has a N-channel IGBT model, but it doesn't include stray inductance and reverse diode. Thus a modified model of IGBT included two stray inductances and a reverse diode, as shown in Figure 3. In Figure 3, $L1$ and $L2$ are the stray inductance. The reverse diode is modeled by a diode, a capacitor and an inductance $L3$. The IGBT module in Figure 3 is an equivalent circuit based on a PNP bipolar transistor and a N-channel MOSFET. It has three parameters: static parameters of MOSFET, static parameters of PNP and dynamic parameters of IGBT. First, we used the static Ic-Vce characteristic to verify the static parameters of PNP and MOSFET. Second, input the dynamic parameters of IGBT(C_{ies}, C_{res}, C_{oes}, TF) based on the datasheet of IGBT. Figure 4 shows the simulation result of dynamic characteristics of IGBT. When switching on the IGBT, we can see the miller platform in Vge. When switching off the IGBT, we can see the oscillation of current and voltage and tail current of Ic.

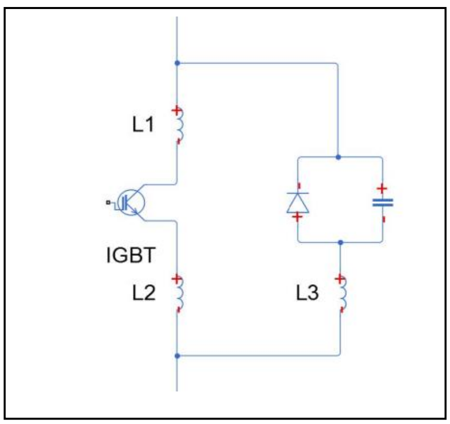


Figure 3. The modified model of IGBT in simulink/Matlab

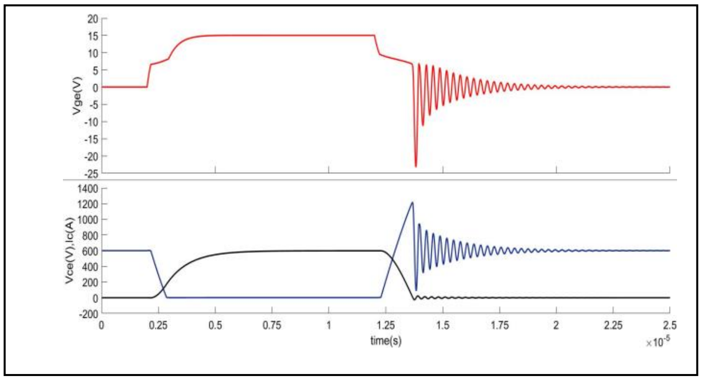
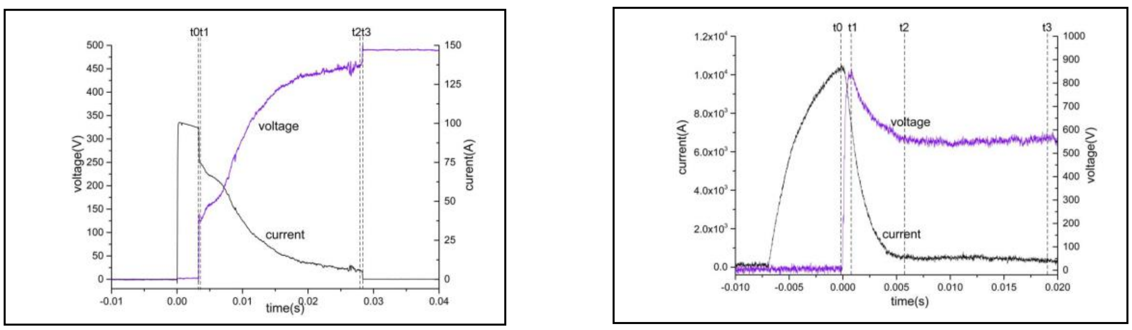


Figure 4. the dynamic characteristics of IGBT

C. *Electric Fuse Model*

A five-stages DC electric fuse model was developed according to typical arc voltage and current experimental results. Figure 5 shows two typical cases. One is an 100 A over-load interruption and the other is a 10 kA short circuit current interruption, both at 500V DC. The arc resistance can be obtained from the arc voltage and arc current. Some typical arc resistance of DC electric fuse is shown in Figure 6. Figure 6 shows that the arc resistance curves are similar at various arc current including not only overload current but also short circuit current. Therefore, the DC electric fuse can be modeled as a variable resistor in arcing period. The variable resistance can be divided into five-stages. The five-stages DC electric fuse model is shown in Figure 7.



(a)overload current result(500V,100A)

(b) short circuit current result(500V,10kA)

Figure 5. the arc voltage and current experimental results of electric fuse

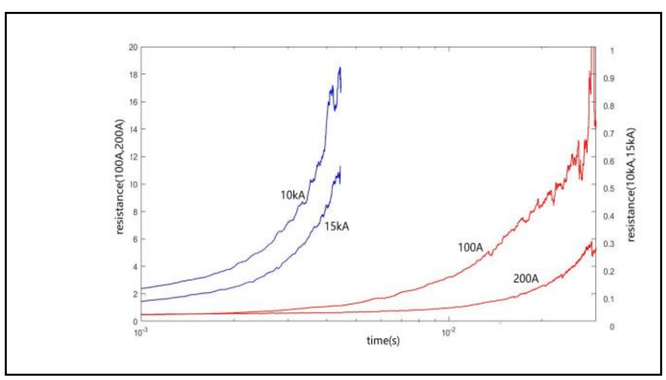


Figure 6. the arc resistance of testelectric fuses

1) 0~t_0: pre-arc stage. In this stage, the fuse resistance can be considered as a resistor with a constant value.

2) t_0~t_1: the arc voltage initiation stage. In this stage, the fuse element starts to melt and its restricted zone starts to induce a voltage rise. This stage is very short, so the resistance can be modeled as a linear resistor. The slope is decided by the pre-arc temperature distribution and the latent heat of fuse element restricted zone. The final value of this stage is decided by the fuse element material.

3) t_1~t_2: the arc stage. From figure 6, one can see that the arc resistance can be modeled as a quadratic polynomial function of time. The multinomial coefficient is decided by the shape of restricted zone, the density of the silica sand and the prospective current.

4) t_2~t_3: the post-arc stage. In this stage, the arc resistance increase rapidly to several MΩ. The arc resistance can be modeled as a linear resistor. The slope and the final value of this stage is decided by the shape of restricted zone, the density of the silica sand and the current in stage 3.

5) t_3 and later: the post-arc insulation stage. In this stage, the resistance is the insulation resistance of fuse.

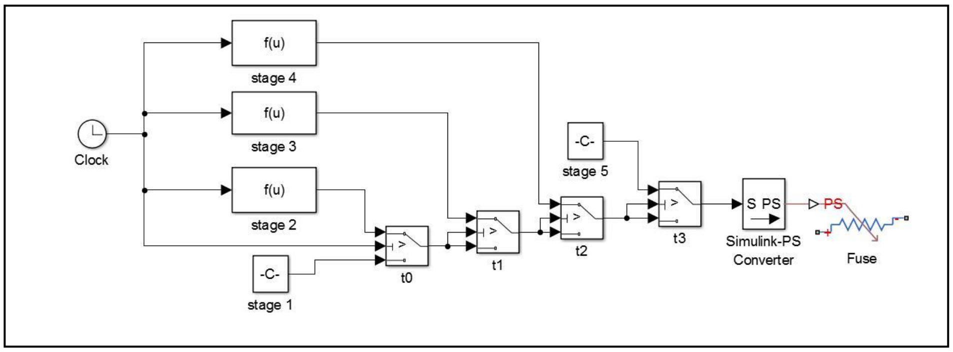
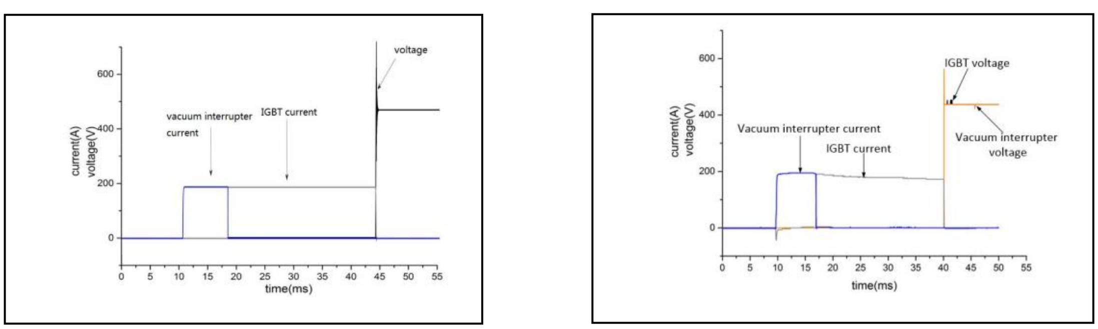


Figure 7. the MATLAB/Simulink model of electric fuse

III. The Model Verifycation

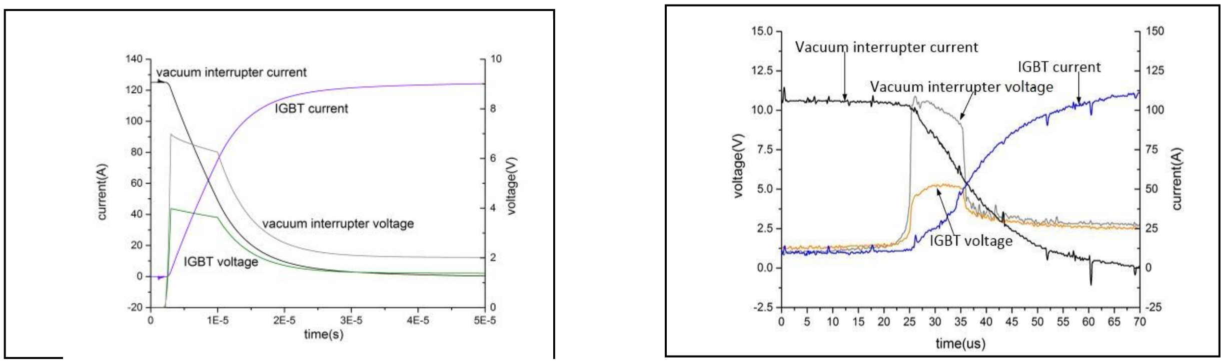
For the hybrid DC apparatus topology shown in Figure 1, a MATLAB/Simulink model was built up. A DC current interruption experiment was carried out to verify the accuracy of the model. The experiment used a *C*-*L*-*R* discharging circuit as a DC voltage source. The DC voltage is 500V, the current was 100A, 200A and 300A, respectively. The current of 100A and 200A was interrupted by IGBT and 300A was interrupted by the electric fuse. The current interruption of 200A was shown in Figure 8. It shows that the current commutated from the vacuum interrupter to IGBT and finally the current was interrupted by IGBT. The current commutation of 200A from vacuum interrupter to IGBT is shown in Figure 9. The current interruption of 300A is shown in Figure 10. It shows that the current commutated from vacuum interrupter to electric fuse and finally it was interrupted by the DC electric fuse. The simulation results were compared with the experimental results. The results showed that the overvoltage error of IGBT interruption was 30%. This was caused by a simulation error of tail current of IGBT; The current commutation time error was 11.1%. This is caused by an error of the commutation circuit inductor. The arcing time error of DC electric fuse was 3.5%. It fits well to the experimental results.



(a)simulation result

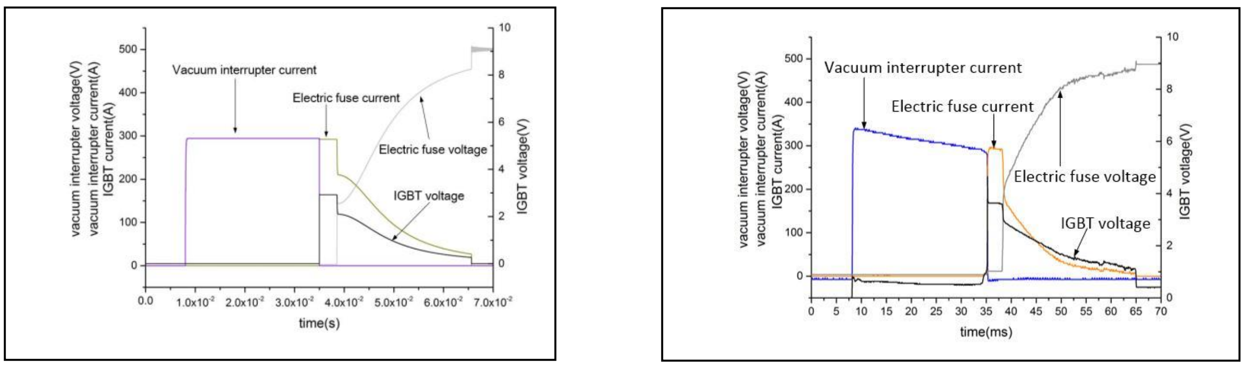
(b) exmeriment result

Figure 8. the current interruption characteristics by IGBT



(a)simulation result (b) exmeriment result

Figure 9. the current commutation characteristics by IGBT



(a)simulation result (b) exmeriment result

Figure 10. the the current interruption characteristics by fuse

IV. Conclusion

This paper builds up a MATLAB/Simulink model for a hybrid DC apparatus that combined with a mechanical switch, a power semiconductor switch and an electric fuse. The model was experimentally validated. The simulation and experiment results shows that:

1)The DC electric fuse can be modeled as a variable resistor by five stages. The arcing time error of the DC electric fuse was 3.5% based on a comparison between the model and experimental result.

2) The model of the hybrid DC apparatus fits well to the experimental results.

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