Comparison and Analysis of DSIM and SIMULINK Simulation Based on MMC System

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***Abstract*—Because of its multi-level output, easy expansion and high modularity, Modular Multilevel Converter (MMC) is increasingly used in many fields such as high-voltage direct current transmission and renewable energy power generation systems. Because there are many switching devices in the MMC system, the electromagnetic interference (EMI) generated by them has a non-negligible impact on the stable operation of the system. At the same time, the current mainstream simulation software is based on time dispersion, and it often takes a long time to simulate power electronic circuits. After adding stray parameters, the circuit exhibits strong rigidity, and the time cost is greatly increased. The DSIM simulation software introduced in this article uses a discrete state event-driven approach, which is different from the previous time-driven approach. This simulation mechanism greatly shortens the time cost and makes the power electronics simulation more convenient. In addition, it can also simulate the transient process of switching devices, so more accurate simulation results can be obtained. This article describes the simulation mechanism of DSIM simulation software and compares the simulation results of DSIM and Simulink to show the outstanding advantages of DSIM software in simulating power electronic circuits.**

Keywords*—*MMC; EMI; DSIM; Simulink

I. Introduction

Along with the continuous development of economy and society, the demand for electric energy is also expanding rapidly. High-voltage and high-power energy conversion has become the development direction of electric energy transmission. Modular Multilevel Converter (MMC) have become a research hotspot due to their advantages of multilevel output, easy expansion and high modularity. However, due to the large number of switching devices in the MMC system, a large amount of high-frequency electromagnetic interference (EMI) will be generated. These electromagnetic interferences have caused great challenges to the stable operation of the system. However, the current domestic and foreign research on MMC's EMI is relatively scarce. Few people use software simulation to study EMI of MMC system. The reason is that the power electronic system is a system in which continuous states and discrete events are mixed with each other. Its switching frequency is generally in the range of Several kilohertz to several hundreds of kilohertz, and the high-frequency electromagnetic interference generated can reach tens of Megahertz. Compared with control time, the time scale spans nearly 100 million times [1]. At present, the mainstream simulation software on the market is based on time discretization. This time-driven method will take a long time to simulate this circuit. After considering the stray parameters, the circuit will show strong rigidity and the time complexity will be greatly increased, which makes it difficult to use the simulation research the EMI of system.

In the field of power electronics, the current mainstream simulation software includes Simulink, Saber and Spice. Saber is a professional circuit simulation software with a powerful and abundant component library. Basically, major component manufacturers provide simulation component models that can be used in Saber to obtain more accurate component simulation results. However, in contrast, the models provided by major manufacturers for Saber are too accurate, so that they have higher requirements on the user's computer, and the simulation is also more time-consuming.

There are also abundant simulation components in Simulink, but these components are basically universal simulation models. There will obviously be a gap between simulation results using these general models and actual simulation results. But the rich graphics processing functions in MATLAB are more conducive to the processing of simulated waveforms.

Spice simulator uses a modified node analysis method to establish circuit equations, providing nonlinear DC analysis, nonlinear transient analysis (real domain analysis) and linear small signal analysis (frequency domain analysis), etc. Among them, transient analysis is the most time-consuming verification method. It usually uses numerical integration to transform nonlinear differential equations into a set of algebraic equations, and then uses Gaussian elimination to solve them. SPICE also has certain limitations. Some circuits cannot be simulated or fail to converge during simulation, especially when used in digital-analog hybrid circuits and pulse circuits.

DSIM software is developed by Tsinghua University together with its industry partner, and is a simulation software specially designed for power electronic systems. It adopts the discrete state event-driven (DSED) simulation mechanism and innovative modeling methods, making full use of the characteristics of the power electronic system, greatly shortening the simulation time. In addition, it can also simulate

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switching transients while simulating large-scale converter systems [2].

This article describes the simulation mechanism of DSIM simulation software and its outstanding advantages in simulating power electronic circuits. Introduced how to build MMC system on DSIM software. Finally, the simulation results of the general control circuit and the MMC system with spurious parameters are obtained, and compared with Simulink, which proves that DSIM software has unparalleled advantages in simulating power electronic circuits.

II. The Basic Principles of MMC and Current Research Status of EMI

Because traditional multilevel converters still have many shortcomings in high-voltage and high-power applications. In 2002, German scholars R.Marquardt and A.Lesnicar first proposed the concept of modular multilevel converter (MMC) and its topology. The outstanding advantage of this structure is the modular innovation, which avoids the excessively high requirements on the device due to a large number of IGBTs connected in series. Since then, extensive research and discussion on MMC have been carried out at home and abroad. Since all the sub-modules of MMC have the same structure and are interchangeable with each other, it is extremely convenient in terms of design, manufacturing, installation, and maintenance. In terms of control, since each sub-module can be independently controlled, it is convenient to control the voltage of the upper and lower bridge arms of each phase to output a voltage waveform that changes according to the sinusoidal law. This solution avoids the problems of switching losses and dynamic voltage equalization caused by the direct series connection of multiple switching devices, and at the same time the harmonic content is also suppressed, and is widely used in the field of high-voltage commutation.

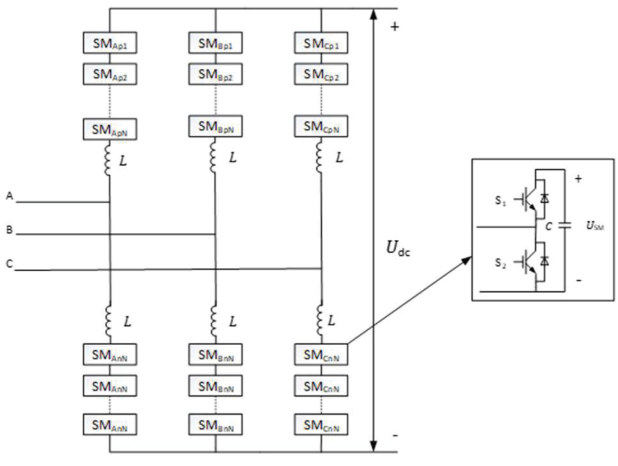


Fig. 1 the topology of MMC.

Fig. 1 shows the topology of a typical three-phase MMC. The sub-module (SM) adopts a half-bridge structure. Each bridge arm has N sub-modules (numbered from 1 to N) and an inductor in series. It can be seen from the circuit topology that one end is the AC side, and the other end is the common DC side. The functions of rectification and inverter can be realized.

Although the current academic research on MMC has become more and more in-depth, and industrial applications are also steadily advancing, there are still few studies on EMI related issues. The electromagnetic interference of the traditional power system is mainly caused by occasional interference such as lightning strikes and switching on. The solutions are mainly grounding, shielding and isolation. For power electronic power systems, the continuous switching of power electronic devices in converters has become the main source of electromagnetic interference, and electromagnetic interference has become the norm. The solution must be the power electronics itself. Especially for MMC-HVDC, due to frequent failures of the flexible converter valve, it has a greater impact on the stability of the power system. State Grid's expert report pointed out that at present, about 80% of the domestic ±500kV DC transmission converter valve failures are caused by electromagnetic compatibility problems. With the application of IGBT-based VSC-HVDC and wide bandgap power electronic devices, electromagnetic compatibility challenges will become more severe. Literature [3] only describes a modeling method for simulating electromagnetic transients of MMC-based HVDC systems. However, the simulation of this kind of converter requires a very large amount of calculation and a long simulation time. Literature [4] studied the improved model of the industrial MMC-HVDC system between France and Spain 400kV network. Although the transient response has been studied in detail, there is insufficient attention to the conducted electromagnetic interference caused by the large number of insulated gate bipolar transistors (IGBT) in MMC. Literature [5] found that the higher dv/dt at the moment of commutation forms electromagnetic interference source through stray capacitance, but under different working conditions, the floating voltage of the sub-module to ground is different, and the position is different. The floating voltage of the sub-module to ground is also different. The sub-module closer to the AC output side needs to withstand a larger voltage jump, while the sub-module closer to the DC bus needs to withstand a smaller voltage jump.

Fig. 2 is a typical structure of the MMC-HVDC system. It can be seen that due to the parasitic capacitance between the transmission line and the ground, the leakage current will flow to the ground through the DC cable. And because each sub-module is encapsulated in the case, and the case and the negative electrode of the sub-module capacitors have the same potential, they have stray capacitance to the ground. This forms a closed loop path [6], creating conditions for the conduction of EMI. In addition, the wide and flat copper bars of the positive and negative bus bars on the DC side will also have stray capacitance to the ground, which cannot be ignored.

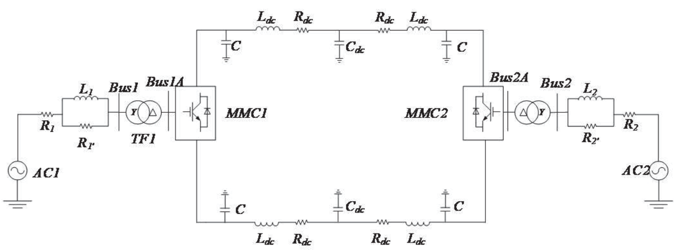


Fig. 2 MMC-HVDC system.

III. Introduction to DSIM Software and its Advantages in Power Electronics Simulation

In power electronic systems, electromagnetic energy is a continuous state variable, and the on-off events of switching devices are discrete events. They are interlaced and mixed to form a complex hybrid system [7]. Due to the extremely short time of the switching event, the transformation process of electromagnetic energy is on the nanosecond time scale, while the dynamic process of the system is often on the second level, with a very large span. Therefore, it is very difficult to analyze the change process of the system simultaneously on two time scales.

At present, for the numerical simulation of purely continuous dynamics systems, the core is the numerical solution of differential equations, and most simulation software on the market also uses this numerical solution [8-9]. This method uses time as an independent variable to establish a dynamic model of the system, and uses time as a discrete criterion to determine the solution method of the system. However, because the time scale span is very large in the hybrid system, the efficiency of this solution method is very low [10].

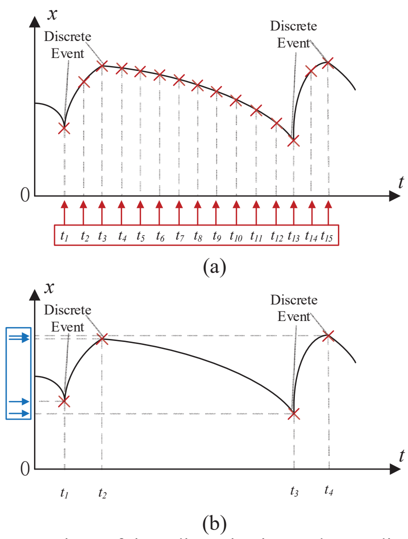


Fig. 3 Comparison of time-discretization and state-discretization simulation approach: (a) discrete-time time-driven, (b) discrete-state event-driven. [2]

The DSIM software uses the discrete state event-driven (DSED)solution algorithm, in which state variables are the active variables that determine the evolution of the system, while the discrete time variables are passive variables that are determined with state changes. This "event"-driven system evolution has greatly increased the speed of simulation [11]. On large time scales, the steady state of the system can be described by the equation of state. At the same time, the small-time scale behavior of the system is also modeled as a small-time scale hybrid system, which is described by a piecewise analytical transient (PAT) model. The different time scale behaviors of such systems are described as different hybrid systems with different mathematical forms (including continuous states and discrete events). The conditions for the occurrence of discrete events in the system and the occurrence of discrete events triggered by large-scale behaviors are described in the model, which makes it possible to solve state discrete and event-driven solutions. Fig. 3 is a comparison diagram of DSED algorithm and traditional time discrete method. It can be seen intuitively from the figure that the DSED algorithm is only solved when the state has "qualitatively changed". This method is automatically triggered by the state itself, and the time step is only the "dependent variable" that follows the state change in the simulation, so the simulation efficiency is greatly improved [3].

IV. MMC System Simulation Based on DSIM Software

A 17-level MMC-HVDC system is built on the DSIM platform. The system adopts the nearest level modulation (NLM), contains an inner loop current controller, can perform closed-loop control, and performs capacitor voltage balance based on a sequencing algorithm. The main circuit of the system is shown in Fig. 4, and the internal circuit of the converter is shown in Fig. 5.

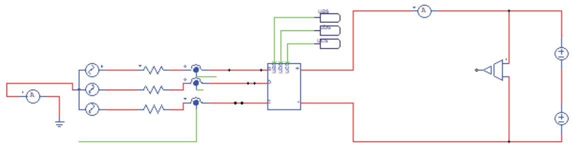


Fig. 4 DSIM simulation model of MMC-HVDC system.

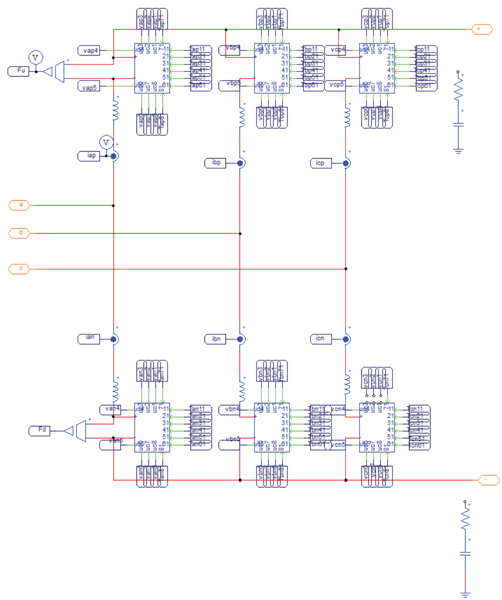


Fig. 5 Internal structure of the converter.

The MMC-HVDC system works in a rectification state, the DC side is not loaded, and the AC side uses 3-ph Sine to replace the grid. The neutral point is grounded. Current Probe is used to measure leakage current and DC bus current. The current transformer transmits the measured current data to the inner loop current controller, and the obtained three-phase reference wave is transmitted back to the main circuit. Each bridge arm inside the converter has an inductance and a Current Sensor for measuring the bridge arm current, which is sent to the modulation system to determine whether the capacitor is charging or discharging. The trigger pulse of each sub-module is sent to the sub-module. Since each sub-module requires two signal control, there are a total of 8 signals input to each sub-module. At the same time, there are eight channels of sub-module capacitance voltage data transmission for subsequent processing. When considering the influence of stray parameters, connect the ground stray capacitance to the DC bus.

Fig. 6 and Fig. 7 are the bridge arms composed of sub-modules in series and the internal structure of the sub-modules. Each bridge arm has 8 sub-modules, so the modulated AC voltage has 9 levels. When considering stray parameters, connect the ground capacitance of the negative pole of the sub-module to the circuit. Since the switch model in the DSIM software device library is provided in the form of a switch module, a single switch device model is not provided, so the IGBT of the sub-module adopts the 2-level Bridge Leg model. The model can also choose three models: Ideal, IGBT/diode, and SiC MOSFET/diode. The corresponding parameters can be set under the IGBT/diode and SiC MOSFET/diode models to obtain more accurate simulation data.

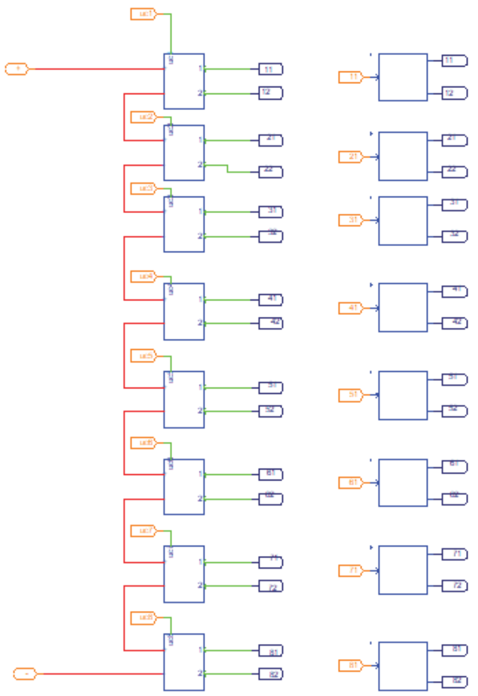


Fig. 6 Structure of bridge arm composed of sub-modules in series.

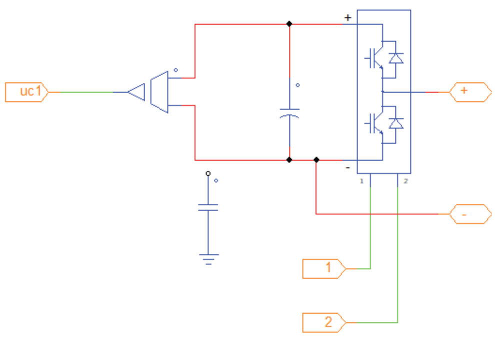


Fig. 7 Internal structure of submodule.

The MMC-HVDC system adopts nearest level modulation (NLM). Combined with the capacitor voltage equalization algorithm, it is determined which sub-modules are input and removed, and the capacitor voltage is balanced. Fig. 8 is the modulation system control circuit.

The modulation system needs to first calculate the number of sub-modules that each bridge arm needs to invest. The capacitor voltage equalization algorithm is essentially a sorting algorithm. Through this algorithm, the capacitor with higher voltage can be discharged and the capacitor with lower voltage can be charged. Finally, a trigger pulse is formed to control the on and off of the IGBT.

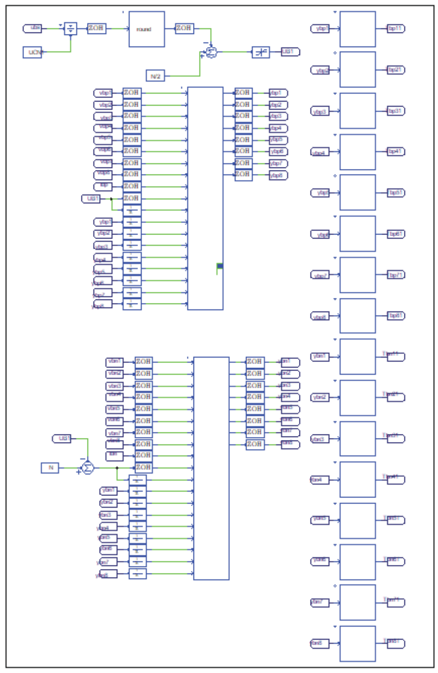


Fig. 8 NLM control system.

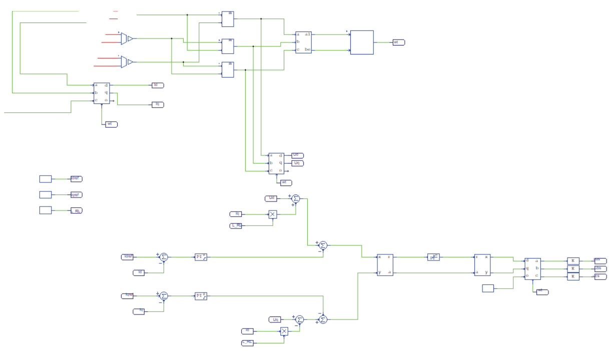


Fig. 9 Closed loop power control system.

The closed-loop power control system is shown in Fig. 9. It can adjust the active and reactive power according to the input i_{d_ref} value and i_{q_ref} value, and generate a reference wave. It involves *d-q* transformation, Parker transformation and PI adjustment, and finally generates three-phase reference waves which is U_{as}, U_{bs} and U_{cs}.

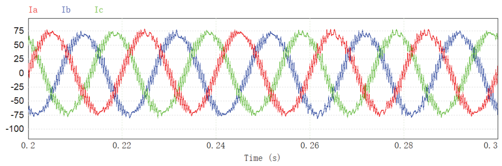
V. Comparative Analysis of DSIM Simulation Software and SIMULINK Simulation Software

In this section, we will build MMC systems of the same scale on the DSIM simulation platform and the SIMULINK simulation platform, and compare the simulation results and simulation speed differences between the two. Then add stray parameters to further compare the difference between the two simulation software simulations of EMI. The main parameters of the system are shown in TABLE I. The system adopts the NLM method and runs on the same computer.

TABLE I THE PARAMETER OF THE SYSTEM

Effective value of AC side line voltage	*DC bus voltage*	*Bridge arm inductance*	*Switching frequency*
490 V/50 Hz	800 V	5 mH	5 kHz
Sub-module capacitance	I_{dref}	I_{qref}	*Stray capacitance*
22 mF	1.414	0	5 nF

A. General simulation model of MMC



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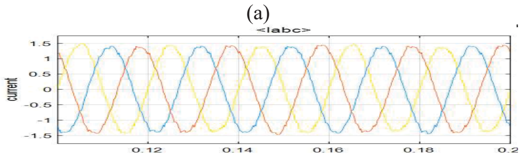
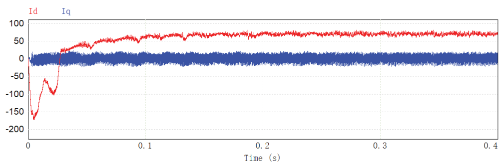


(b)

Fig. 10.1 AC side three-phase current of AC side: (a) DSIM, (b) SIMULINK.



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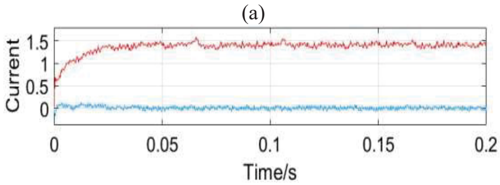

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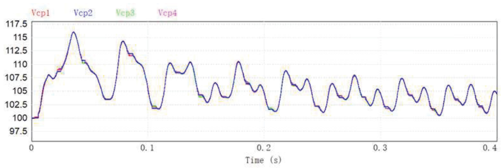
Fig. 10.2 I_d and I_q: (a) DSIM, (b) SIMULINK.



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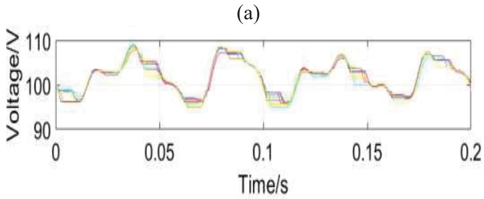
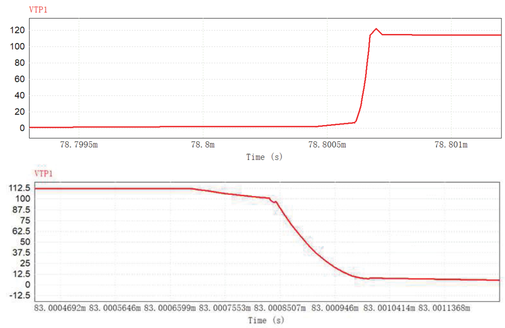


(b)

Fig. 10.3 capacitor voltage of Sub-module: (a) DSIM, (b) SIMULINK.

Comparing the simulation results of Simulink software and DSIM software, the simulation results of the two are basically the same. Both I_d and I_q can follow the set value well, and the fluctuation range of the capacitor voltage of the sub-module can also be stabilized within 5%. Therefore, for general control circuit simulation, both simulation software can give corresponding results smoothly. For the simulation speed, when the system running time is 0.4 s, and the step length is 0.1μs, the simulation time of Simulink software is 8 minutes and 20 seconds. DSIM simulation software does not need to set the step length due to its adaptive step length, and its simulation time is 36 seconds. The difference between the two is nearly 14 times. It can be seen that the discrete-state event-driven simulation mechanism adopted by DISM simulation software is effective and can greatly increase the simulation speed, and the results will not be affected.



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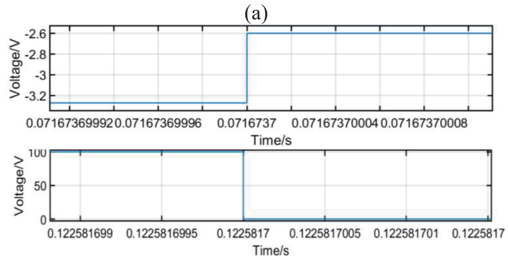
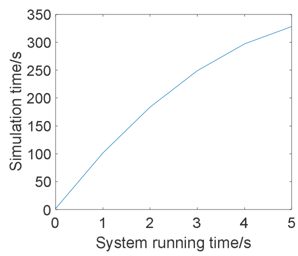


(b)

Fig.10.4 on-off moment of IGBT: (a) DSIM, (b) SIMULINK.

Comparing the simulation results of the two simulation software, we can see that the DSIM software can simulate the transient change process of the IGBT, while the Simulink IGBT is an ideal model, and its switching action changes instantaneously. Therefore, the IGBT model of DSIM is closer to the actual situation, and the simulation results are more accurate.



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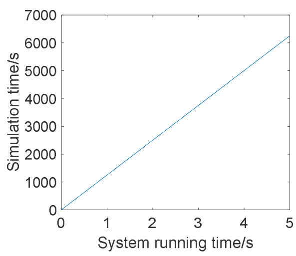
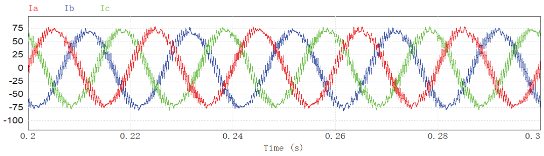


(b)

Fig.11 Simulation time comparison: (a) DSIM, (b) SIMULINK.

Since Simulink software adopts a time-driven simulation mechanism, the simulation time changes in direct proportion to the system running time. The DSIM software adopts the event-driven simulation mechanism, so its advantages will be more obvious when the simulation is for a long time.

B. MMC simulation model with stray parameters



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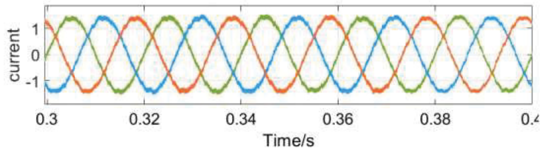
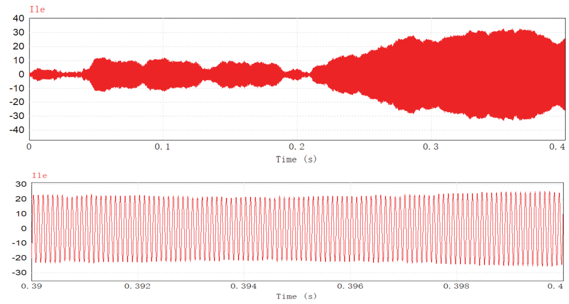


(b)

Fig. 12.1 AC side three-phase current of AC side: (a) DSIM, (b) SIMULINK.



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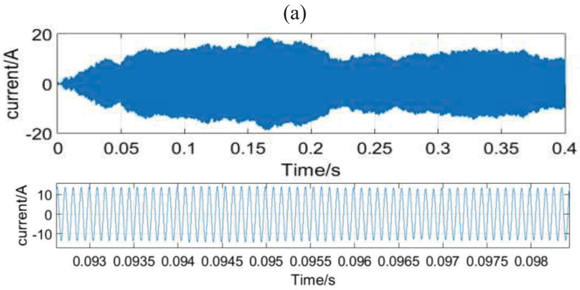
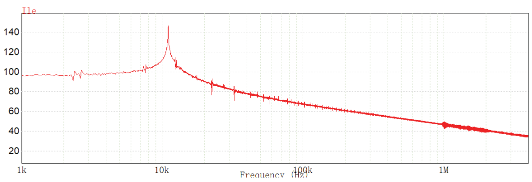


(b)

Fig. 12.2 Leakage current: (a) DSIM, (b) SIMULINK.



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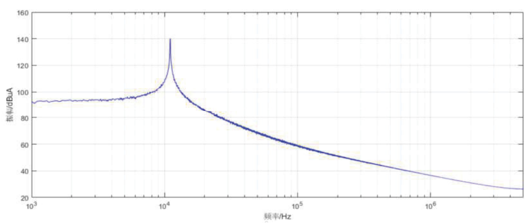

(b)

Fig. 12.3 FFT of leakage current: (a) DSIM, (b) SIMULINK.

It can be seen from the simulation results that there is not much difference between the two simulations. The magnitude of the leakage current is within 20 A, and the spectrum of the leakage current has a spike around 10 kHz and its amplitude is 140 dBμA. But DSIM software can capture the details. The spectrum obtained by the DSIM software has more high-order harmonics with less amplitude, which are ignored by the Simulink software.

VI. Conclusion

This article first analyzes the working principle of MMC. Due to its unique advantages, it is used in more and more occasions. However, due to the electromagnetic interference of the system, the switching devices are often damaged, which seriously threatens the safe and stable operation of the system. However, due to the large number of MMC sub-modules and the complexity of the system, traditional simulation software takes a long time to simulate, and there are also varying degrees of discrepancies from the actual situation. DSIM software uses discrete state event-driven simulation mechanism to realize high-speed simulation. At the same time, its innovative modeling method also makes the results more accurate. Finally, through comparison with Simulink, the unique advantages of DSIM software are verified.

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